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**Impact and explosion crater ejecta, fragment size, and velocity**

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**Impact and explosion crater ejecta**

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## ABSTRACT

A model was developed for the mass distribution of fragments that are ejected at a given velocity for impact and explosion craters. The model is semi-empirical in nature and is derived from (1) numerical calculations of cratering and the resultant mass versus ejection velocity, (2) observed ejecta blanket particle size distributions, (3) an empirical relationship between maximum ejecta fragment size and crater diameter and an assumption on the functional form for the distribution of fragments ejected at a given velocity. This model implies that for planetary impacts into competent rock, the distribution of fragments ejected at a given velocity are nearly monodisperse, e.g. 20% of the mass of the ejecta at a given velocity contain fragments having a mass less than 0.1 times a mass of the largest fragment moving at that velocity. Using this model, we have calculated the largest fragment that can be ejected from asteroids, the moon, Mars, and Earth as a function of crater diameter. Upon formation of a 50 km diameter crater on an atmosphereless planet having the planetary gravity and radius of the Moon, Mars, and earth, fragments having a maximum mean diameter of  $\approx 1\text{ km}$ ,  $10$  to  $10^2\text{ m}$ , and  $3\text{ m}$  could be launched to escape velocity in the ejecta cloud. In addition, we have calculated the internal energy of ejecta versus ejecta velocity. The internal energy of fragments having velocities exceeding the escape velocity of the moon ( $\sim 2.4\text{ km/s}$ ) will exceed the energy required for incipient melting for solid silicates and thus, constrains the

maximum ejected solid fragment size.

## Introduction

In this paper we have developed models for the distribution of fragments that are ejected at a given velocity for both impact and explosion cratering. The results from these models have application to the physics of planetary accretion and the origin of meteorites.

Upon accretion of a planet via the process of planetesimal impact on the surface, most (80 to 80% depending on velocity) of the energy of the infalling planetesimal is transferred into thermal energy of a shocked planetary material [O'Keefe and Ahrens, 1977a]. Virtually all of the planetary target material which is taken up in the resulting cratering motion receives this internal energy and a large fraction of this material eventually moves upward producing ejecta. Although all of the ejecta by definition is set into upward motion, depending on the size of the resulting crater and planetary gravity, only a portion of the material is projected outside the transient crater cavity. The amount of thermal energy deposited in the ejecta which is retained by the planet will depend on: 1) how quickly the ejecta becomes buried, 2) how much energy is lost to space via radiation, and 3) whether or not a coaccreting atmosphere [Lange and Ahrens, 1982] absorbs the thermal energy of ejecta by conduction and then reradiates it [Safronov, 1972; Kaula, 1979]. For a given impact accretional history, the above processes depend explicitly on size and velocity of the impacting bodies and the resulting mass of ejecta launched at various velocities as well as the size distributions of the particles that are ejected.

The degree to which the 20 to 30% of the energy of the impact which resides in the kinetic energy of the impact ejecta [O'Keefe and Ahrens, 1977a] can be coupled into the coaccreting atmosphere [Lange and Ahrens, 1982] or coupled as thermal energy in the planetary regolith depends on the size and velocity distribution of the ejecta. In addition, the depth and range of surface layer stirring resulting from the impact curtains of secondary ejecta [Oberbeck, 1975] is also a function of the size and velocity distribution of ejecta.

The understanding of the origin of several meteorite types which may be impact derived fragments from other planetary surfaces depends upon the understanding of impact mechanics and explicitly the relationship between fragment size and velocity of ejection.

A recent discovery of a meteorite, ALHA (81005), in the Antarctic [Ostertag and Ryder, 1983; Treiman and Drake, 1983; and Warren et al., 1983] has physical and chemical characteristics which imply lunar origin. The issues associated with this discovery are the consistency of this find with the orbital and capture mechanics and with the cratering mechanics.

The origin of the SNC (shergottites, nakhrites, and chassignites) class of meteorites is more difficult to understand. The physical characteristics imply a Martian origin which would require an ejection velocity greater than 5 km/s to be accreted by the earth [Nakamura et al., 1977; McSween et al., 1979; Nyquist, 1982; Wasson and Wetherill, 1979; Bogard and Johnson, 1983]. This high ejection velocity along with requirements that the ejecta size be large

(>10m) has spawned considerable debate by those who have been examining the impact dynamics [Gault, 1983; Singer, 1983; Melosh, 1983; Nyquist, 1983; Ahrens and O'Keefe, 1983].

The impact ejection of fine dust into the Earth's atmosphere has been proposed as a mechanism for extinctions that occurred at the end of the Cretaceous [Alvarez et al., 1980]. This event may have produced a drastic short-term effect on climate which caused the sudden and dramatic extinction of many forms of life. Models of the effect of injection of very large amounts of impact-induced dust into the stratosphere and upper troposphere [Toon et al., 1982; Gerstl and Zardecki, 1982] depend critically upon the theoretical cratering models for the total amount of dust ejecta available and the size distributions as a function of altitude [O'Keefe and Ahrens, 1982; Jones and Kodis, 1982].

The relationship of ejecta particle size for impact and explosions on rock has received considerable experimental and some recent theoretical attention.

Gault et al. [1963], and Fujiwara et al. [1977, 1980], and Lange and Ahrens [1982, 1983] have experimentally measured the size distributions of ejecta from impacts on various geological media. Data pertaining to ejecta from chemical and nuclear explosions have recently been summarized by Schoutens [1979]. Most models of cratering flow assume a continuum, thus ejecta size is not explicitly obtained. The lack of methods for calculating the particle size (and mass at a given size and given velocity) is a major shortcoming. Grady and Kipp [1980] and Shockley et al. [1974] have made inroads on this problem and have derived analytic and

numerical models of dynamic fracture size distributions based on statistical theories of flaw-induced failure using analytical and computational methods, respectively. Recently Melosh [1983] has proposed a theory which predicts both the size and velocity of the failure of the spall failure surface ejecta from around impacts and has discussed this process in relation to the question of obtaining unshocked samples from other planetary surfaces via impact.

The present study was motivated by the need to obtain a relationship between particle size, ejecta velocity and ejecta mass at different velocities for impact and explosion craters which are larger than those easily studied in the laboratory (0.1 to 1 meter).

### Approach

In this paper we have developed a technique for determining the distribution of fragments that are ejected at a given velocity. The approach taken differs from the approaches of Shockley [1983], Grady and Kipp [1980] in that we have chosen to solve an inverse problem. The problem is as follows. There is a considerable data base on the distribution of fragments in the ejecta blankets of impact, explosion and nuclear craters. In addition, we know from detailed hydrodynamic calculations of impact induced flow fields [O'Keefe and Ahrens, 1983, 1982, 1977b], the amount of mass ejected at a given velocity. By making the assumption that the distribution of fragments that are ejected at a given velocity is a function of the ejection velocity, an expression can be developed which relates the distribution of fragments in the ejecta blanket to the amount of mass ejected at a given velocity and the unknown

distribution of fragments ejected at a given velocity.

We discuss below the: 1) experimental data base for the distribution fragments in the ejecta blankets of impact, explosion, and nuclear craters, 2) the hydrodynamic calculations of the impact induced flow fields and the amount of mass ejected at a given velocity, and 3) the details of the fragmentation theory.

#### Experimental data

The distribution of fragments from both natural and laboratory impacts and nuclear and chemical explosions have been measured by a number of researchers and have been summarized by Hartmann [1969], Seebaugh [1975], and Schoutens [1979]. Hartmann [1969] showed that these distributions could be fit by a power law function:

$$\frac{M'_c}{M_T} = \left( \frac{m}{m_b} \right)^{\alpha/3} \quad (1)$$

or alternatively

$$\frac{M'_c}{M_T} = (A/A_b)^\alpha \quad (2)$$

where  $M'_c$  is the cumulative mass having individual fragments not exceeding a mass  $m$ , or a diameter  $A$ , and  $M_T$  is the total mass of ejecta. Here,  $m_b$  and  $A_b$  is the maximum mass and maximum mean diameter of the ejecta fragments. Equation (1) may be written in the complementary form:

$$M_C/M_T = [1 - (m/m_b)^{\alpha/3}] \quad (3)$$

where  $M_C$  is now the cumulative mass in ejecta having particles with a mass greater than  $m$ .

The distributions represented by Eqs. 1-3 are similar in form to those found in the case of crushing and milling of rocks. The exponents of the power law are indicative of severe crushing and multiple fragmentation. The exponent  $\alpha$  for impact events is found to be in the range from 0.4 to 0.55 and the ejecta distribution for many nuclear and chemical explosions have similar distributions as impact events (Fig. 1).

The power law distributions have both lower and upper limits of fragment size. Gault et al. [1963] determined these limits from a number of laboratory and field experiments. Shoemaker [1962] employed telescopic measurements of the distribution of secondary crater sizes from the lunar crater, Copernicus, to determine the relation between velocity and ejecta size. Gault et al. [1963] developed a relationship between the largest fragment in the ejecta blanket and the crater size. This is shown in Fig. 2 and a fit to the data in the large impact regime is given by:

$$M_b = 0.2 M_f^{0.8} \quad (4)$$

Implicitly, Eq. 4 implies that as larger craters are excavated on a planetary surface, larger and that more coherent rocks are exhumed. Hence, the size of the largest ejecta fragment increases with crater size. The lower limit on fragment size which satisfies a power law fit, has not been described in detail. However, the impact experiments of Gault et al. [1963] provide some insight. Referring to Fig. 1, the amount of mass in fragments less than  $10^{-3}$

cm decreases rapidly with decreasing particle size. This could be the result of a decrease in the number of activated flaws that have spacings of less than  $10^{-3}$  cm in the rock. Another mechanism which may possibly explain the deficit of smaller particles is the coagulation of fine particles prior to sampling. The deficit of fine particles, relative to a power law fit is not unique to either impact ejecta or ejecta from contained explosions (e.g. Piledriver). Similar deficits in the cumulate mass of particles less than  $10^{-8}$  to  $10^{-3}$  cm diameter have been observed in the ejecta from several high explosive tests carried out on the surfaces of various geologic terranes [Schoutens, 1979].

#### Impact flow field calculations

O'Keefe and Ahrens [1983, 1982, 1977b] have calculated using two dimensional elastic-plastic hydrodynamic code calculations, the cumulative relative mass of ejecta at a given velocity or lower, versus, velocity (Fig. 3) for the case of silicate and ice projectiles impacting a silicate halfspace at 5 to 45 km/sec for projectiles with densities ranging from 0.01 to 2.9 g/cm<sup>3</sup>. Between ejection velocities of  $V = 10^{-3}$  to 2 km/sec, all of these calculations are closely described by an expression of the form:

$$\frac{M'_{cv}}{M_T} = (V/V_{min})^{-\xi} \quad (5)$$

for  $V_{min} < V < V_{max}$  where  $\xi = 1.36 \pm 0.02$  and  $V_{min}$  is minimum  $V_{max}$  is the maximum velocity ejection velocity. The physical interpretation of  $V_{min}$  is that it is the minimum ejection velocity for the crater, and it should be consistent with the total mass ejected

from the crater,  $M_T$ . The value of  $\xi = 1.36$  obtained for impact into silicates is close to the  $1.22 \pm 0.02$  value obtained by Housen et al. [1983] for impacts in quartz sand.

Again, we can write a complementary relation instead of (5) as:

$$\frac{M_{cv}}{M_T} = 1 - (V/V_{min})^{-\xi} \quad (6)$$

where  $M_{cv}$  is the cumulative mass having velocity greater than  $V$ . A similar relation based on dimensional analysis was recently derived by Housen et al. [1983]. In order to non-dimensionalize the velocity,  $V$ , Housen et al. divided  $V$  by  $\sqrt{gD/2}$  where  $D$  is crater diameter, and  $g$  is planetary gravity. We have alternatively assumed for the size of craters of interest gravity scaling is appropriate. We assume that:

$$V_{min} = \sqrt{2g d_{min}} \quad (7)$$

where  $d_{min}$  is the depth of the crater and  $V_{min}$  is then just the minimum velocity required to lift ejecta to the rim of the crater. We estimate  $d_{min}$  by assuming:

$$d_{min} = \left( \frac{50M_T}{\pi \rho} \right)^{1/3} / K \quad (8)$$

where  $\rho$  is the density of the silicate planet and the factor,  $K$ , the crater diameter to depth ratio varies from 5 [Pike, 1974] to values possibly as high as 20.

One constraint on fragmentation is when the internal energy of the impact exceeds the energy required to melt or vaporize the

planetary material. We have examined this issue and have plotted the ratio of the internal energy in the ejecta to the incipient melt energy as a function of ejection velocity. Referring to figure 4, the ejecta internal energy is an appreciable fraction of the melt energy, independent of impact velocity, for ejection velocities greater than 1 km/s. In the case of impacts at high velocities ( $> 30$  km/s) into porous regoliths, this fraction is high for nearly all ejecta velocities.

#### Fragmentation theory

The objective of the theory was to determine the distribution function of the fragments ejected at a given velocity. This is accomplished by establishing a relationship between measured distribution functions for fragments in crater ejecta blankets and calculated functions describing the amount of mass ejected at a given velocity and the unknown distribution of fragments ejected at a given velocity.

By definition the cumulative amount of mass  $M_c$  of fragments of mass greater than  $m$  is given by

$$M_c = \int_{m_{\min}}^V \frac{\partial M_{ev}}{\partial V} f(m, m_{bv}(V)) dV \quad (9)$$

where  $\frac{\partial M_{ev}}{\partial V}$  is the amount of mass ejected at velocities between  $V$  and  $V+dV$ , and  $f(m, m_{bv}(V))$  is the unknown distribution of fragments ejected at  $V$ .

The expression for the amount of mass ejected at a given velocity,  $M_{ev}$ , can be determined from the curve fit expressions to the

cumulative amount of mass ejected at velocities greater than  $v$  given by equation 8.

$$\frac{\partial M_{cv}}{\partial V} = \xi M_T \left[ \frac{V}{V_{\min}} \right]^{-(\xi+1)} \quad (10)$$

The key assumption in the theory is that functional form of distribution of fragments ejected at a given velocity has the same form as the distribution function of the fragments in the ejecta blanket. With this assumption the cumulative amount of mass of fragments of mass greater than  $m$  is given by

$$f(m, m_{bv}(v)) = \left[ 1 - \left( \frac{m}{m_{bv}} \right)^{\frac{\beta}{3}} \right] \quad (11)$$

where  $m_{bv}$  is mass of the largest fragment ejected at a given velocity  $v$ , and  $\beta$ , is an unknown parameter to be determined.

In addition, we assume that the mass of the largest fragment ejected at a given velocity is a function of the velocity of ejection and is given by

$$\frac{m_{bv}(v)}{m_b} = \left[ \frac{v}{V_{\min}} \right]^{-\delta} \quad (12)$$

where  $\delta$  is an unknown parameter to be determined.

Now substituting equations (10), (11), and (12) into Eq. 9 and evaluating the integral we have

$$\frac{M_c}{M_T} = \left[ 1 - \left( \frac{m}{m_b} \right)^{-\frac{\xi}{\delta}} \right] + \left( 1 + \frac{\delta \beta}{3 \xi} \right)^{-1} \left[ \left( \frac{m}{m_b} \right)^{-\frac{\xi}{\delta}} - \left( \frac{m}{m_b} \right)^{\frac{\beta}{3}} \right] \quad (13)$$

In terms of mean fragment diameter

$$\frac{M_c}{M_T} = \left[ 1 - \left( \frac{A}{A_b} \right)^{\frac{3\delta}{\alpha}} \right] + \left( 1 + \frac{\delta\beta}{3\xi} \right) \left[ \left( \frac{A}{A_b} \right)^{-\frac{3\xi}{\alpha}} - \left( \frac{A}{A_b} \right)^\beta \right] \quad (14)$$

The above expression has been compared to experimental cumulative fragment mass versus relative diameter data and the simple power law fits to that data. The difference between these are only small when

$$\delta = + \frac{3\xi}{\alpha} \quad (15)$$

and when the parameter  $\beta > 2$ . The result of varying  $\beta$  is shown in figure 5, where we compare the results to the data of Gault et al. [1963] and Fujiwara et al. [1977].

Finally, we can also evaluate  $\delta$  using Eq. 15. Allowing  $\xi$  to vary from 1.34 to 1.38 and  $\alpha$  to vary from 0.53 to 0.42 we obtain values of  $\delta$  in the range + 9.9 to + 7.6.

### Applications and Conclusions

The meaning of the value of  $\beta$  appropriate for the constant in Eq. 12 is illustrated by the plot of Fig. 6. The value of  $\beta = 2$  implies that only 20% of the mass of all the ejecta traveling at a given velocity,  $V$ , have particle masses less than 0.1 times the mass of the largest fragment traveling at this velocity. Qualitatively, this result implies that for each velocity the fragment size in the ejecta cloud at that velocity is nearly monodispersed.

Equation 1 may be directly applied to provide an upperbound on the amount of very fine ejecta ( $< 1 \mu\text{m}$ ) which could be launched as a result of impact of a very large projectile as, for example, that

proposed by Alvarez et al. to have impacted the earth at the end of the Cretaceous and affected the global climate and possibly evolution. Using the estimated crater size of Schmidt and Holsapple [1982] implies that the mass total crater ejecta in the  $10^{18}$  to  $10^{21}$  g range thus a range of maximum ejecta fragment mass of  $10^{14}$  to  $10^{16}$  g (Eq. 4). Equation 1 then yields an estimate of the maximum mass fraction of ejecta having a mass less than  $10^{-12}$  g ( $<1\mu\text{m}$  diameter) in the range  $10^{-5}$  to  $10^{-4}$  of the total ejecta mass or  $10^{13}$  to  $10^{17}$  g. Calculations of Gerstl et al. require  $10^{16}$  g to completely reduce the sunlight by a factor  $10^{-5}$ , thus reductions by at least an order of magnitude are feasible by solid fragments from that event. Note that melt or condensed vapor may also make a large contribution to the inventory of very small particles ( $<1\mu\text{m}$ ).

Using the values of  $\delta = +7.6$  to  $+9.9$  in Eq. 12 yields values of the launch velocity of the ejecta which is  $\approx 200$  to  $500$  times  $V_{\min}$ . Plausible values  $V_{\min}$  are  $10^{-3}$  to  $10^{-1}$  km/sec. Hence, all of the ejecta is initially launched to speeds of at least 1 km/sec and although ballistically it cannot be carried far in the atmosphere it carried along with the air splash from such an impact (e.g. O'Keefe and Ahrens, 1982), and will reach the upper atmosphere. It should also be noted that the depth of a plausible crater from such an event on the order of 0.1 to 10 km for the diameter range 2 to 200 km, and thus can approach the atmosphere scale height (7 km). Hence, we infer that virtually all of the fines will be launched to the upper atmosphere.

We have used Eqs. 2, 4, 5, 7, 8, and 12 to calculate the largest ejecta fragment that can be launched to escape velocity via impact

from the assumed rock surface of the Ceres (the largest asteroid), Moon, Mars, and Earth. The uncertainty shown in the figure results largely from the uncertainty in the parameter of  $\delta$  (Eq. 12). For a crater of a diameter of 10 km on Ceres, fragments of  $\sim 10$  m diameter would just exceed the escape velocity of 480 m/s. For a crater of a diameter of 50 km on the Moon, fragments moving at the 2.4 km/s escape velocity could be as large as 1 km in diameter according to Eqs. 4 and 12, whereas for an atmosphere-free object with the escape velocity of the earth, a 50 km crater could launch only a 3 m diameter ejecta fragment to escape velocity. The largest fresh martian craters have diameters of  $\approx 50$  km. Fig. 6 indicates the ejecta fragments no larger than  $\approx 10^1$  to  $10^2$  m (with an uncertainty of an order of magnitude) could be launched to 5 km/s from Mars.

When we include the effect of melting and vaporization at high ejection velocities this imposes a severe constraint on the fragment size produced as a result of all impacts except those occurring very obliquely (e.g.  $< 10^\circ$ ) [Melosh, 1983; Singer, 1983; O'Keefe and Ahrens, 1977b]. Referring to figure 4, we see that for ejection velocities greater than  $\approx 2$  km/s, the average internal energy of the ejecta is greater than the incipient melt energy. The implication of these results are that for planets having escape velocities greater than the moon, the ejecta from all impacts, except possibly highly oblique impacts, will be melted. The solid and melt/vapor regimes are indicated in figure 7. In the case of impact ejection from Mars, consideration of the enhanced ejection of material from very oblique impacts or possibly from volatile-

bearing media [Wasson and Wetherill, 1979; O'Keefe and Ahrens, 1983] may allow some solid impact ejecta to be launched and escape from Mars.

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### Figure Captions

Fig. 1. Ejecta size distribution from hypervelocity impact experiments on basalt [Gault et al., 1963], particle size distributions from (10 kton) contained underground explosion, Piledriver [Seebaugh, 1975], and various surface and nuclear and chemical explosions [Schoutens, 1979]. Explosive yield in  $10^3$  tons of TNT indicated in parenthesis.

Fig. 2. Mass of the largest fragment versus total ejected mass for explosive and impact cratering events [after Gault et al., 1963].

Fig. 3. Cumulative ejecta mass at velocity less than  $V$  versus ejecta velocity. Calculations for impacts of solid silicate and ice at 5 km/sec are indicated.

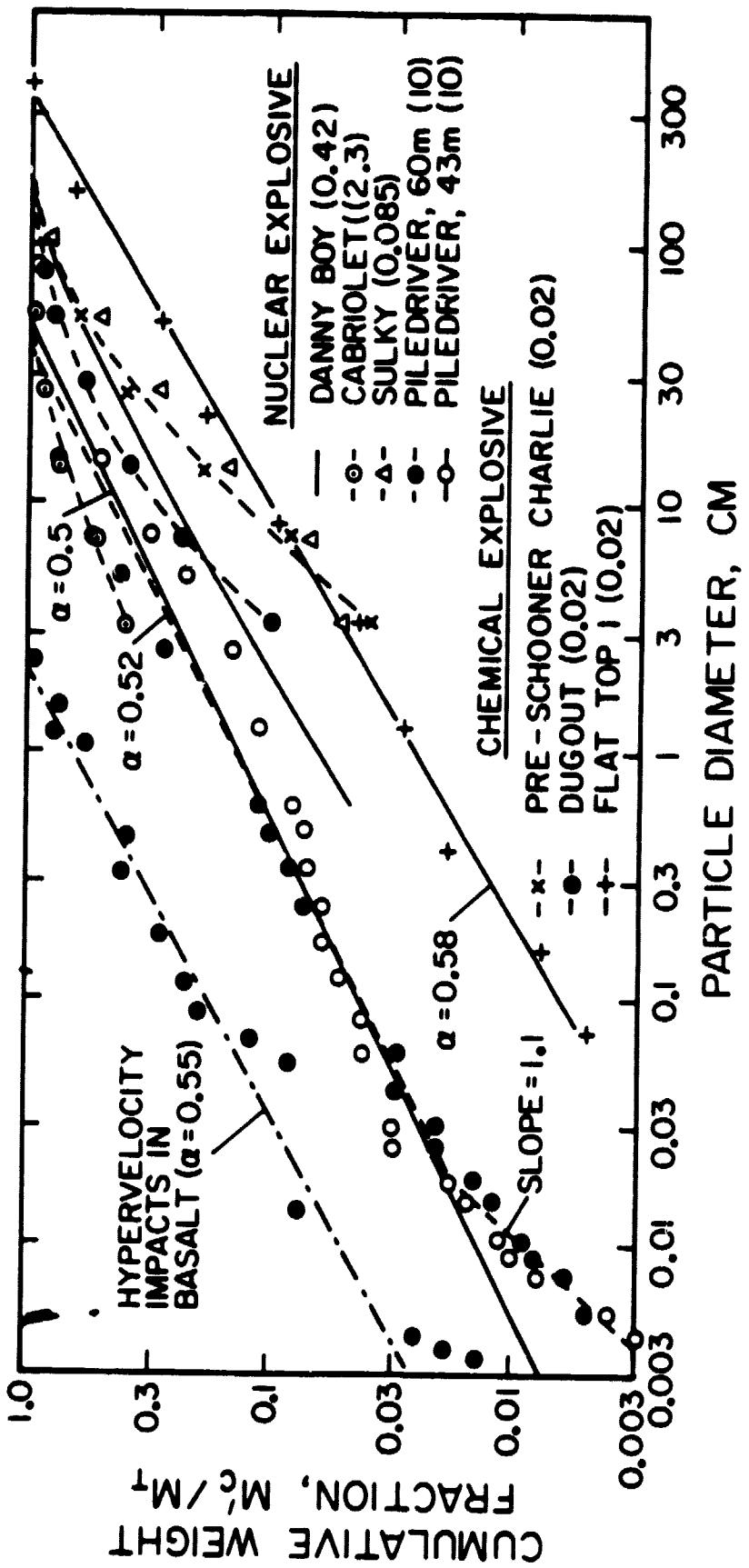
Fig. 4. Ratio of the internal energy of ejected fragments to incipient melt energy as a function of ejection velocity. Impact velocities are 5 and 30 km/s onto solid and porous (31%) silicate planetary surfaces.

Fig. 5. Normalized ejecta cumulative mass distribution versus cumulative mean ejecta size at a given velocity for different values of  $\beta$ . Curves a, b, c, and d correspond to  $\alpha = 0.48$  and values of  $\beta = 0.2$ , 0.5, 2, and 5, respectively.

Fig. 6. Normalized ejecta cumulative mass distribution versus mean diameter for impact experiments on basalt. Theoretical values of distribution calculated from Eq. 13 for different values of  $\beta$ .

Fig. 7. Calculated maximum ejecta particle size versus impact crater diameter for escape from the atmosphereless planets having the mass and radius of the asteroids (Ceres), Moon, Mars and earth.

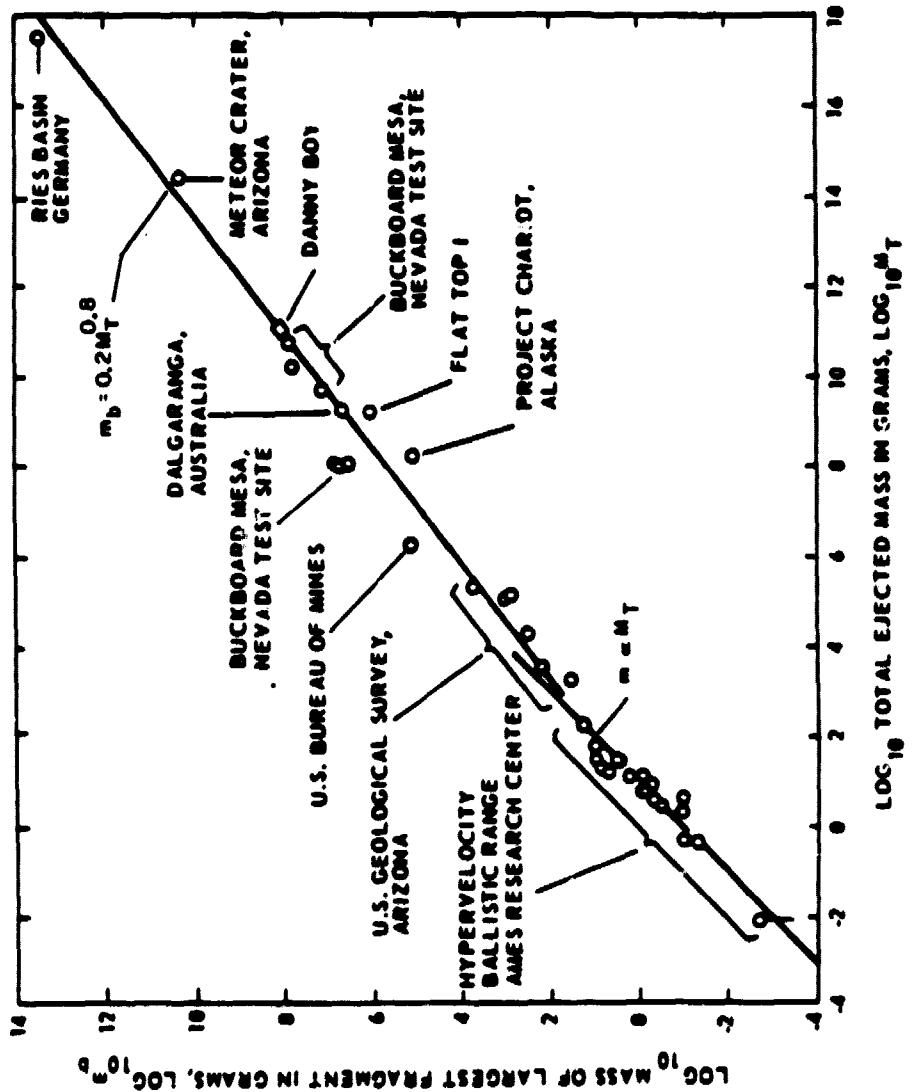
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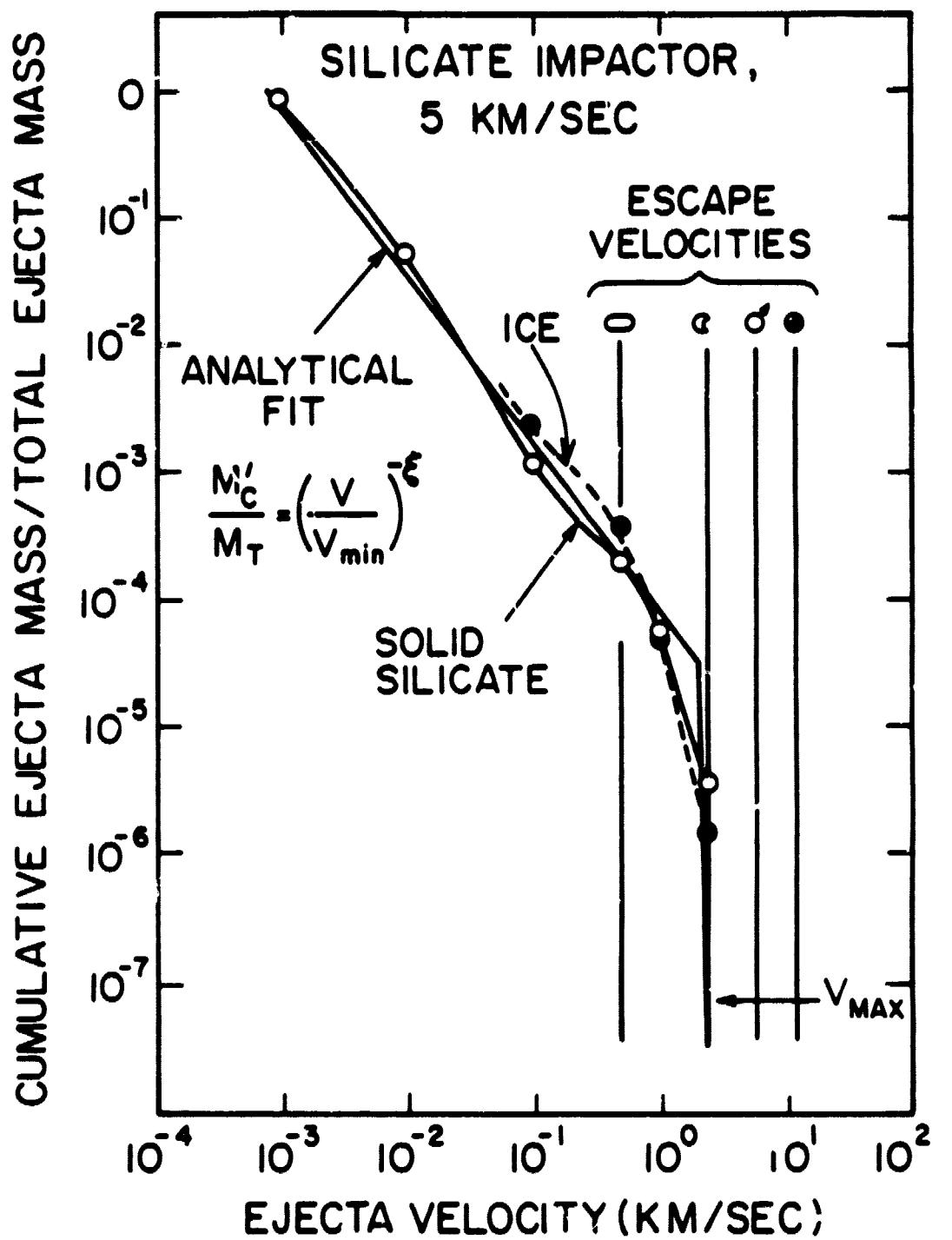
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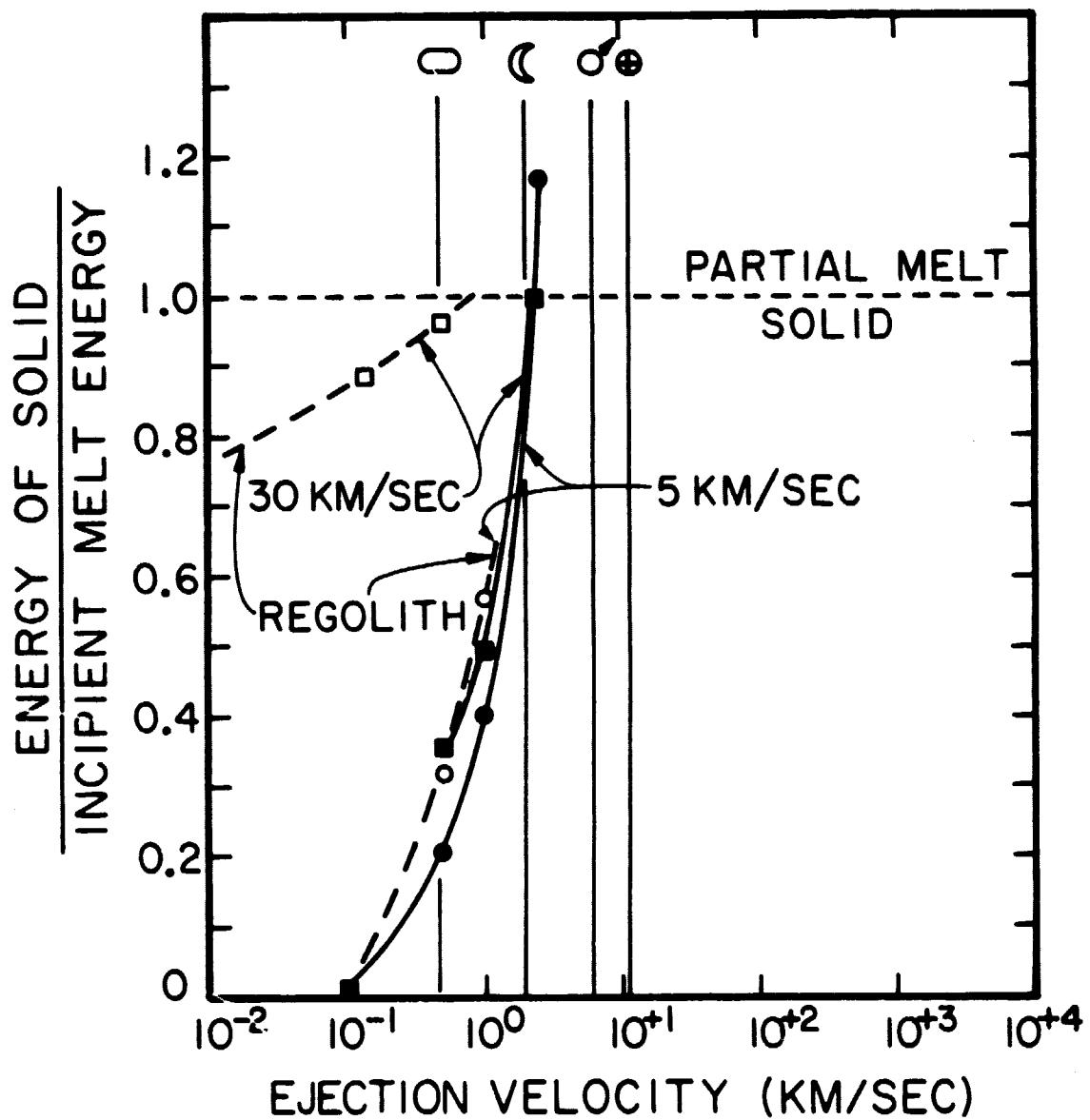


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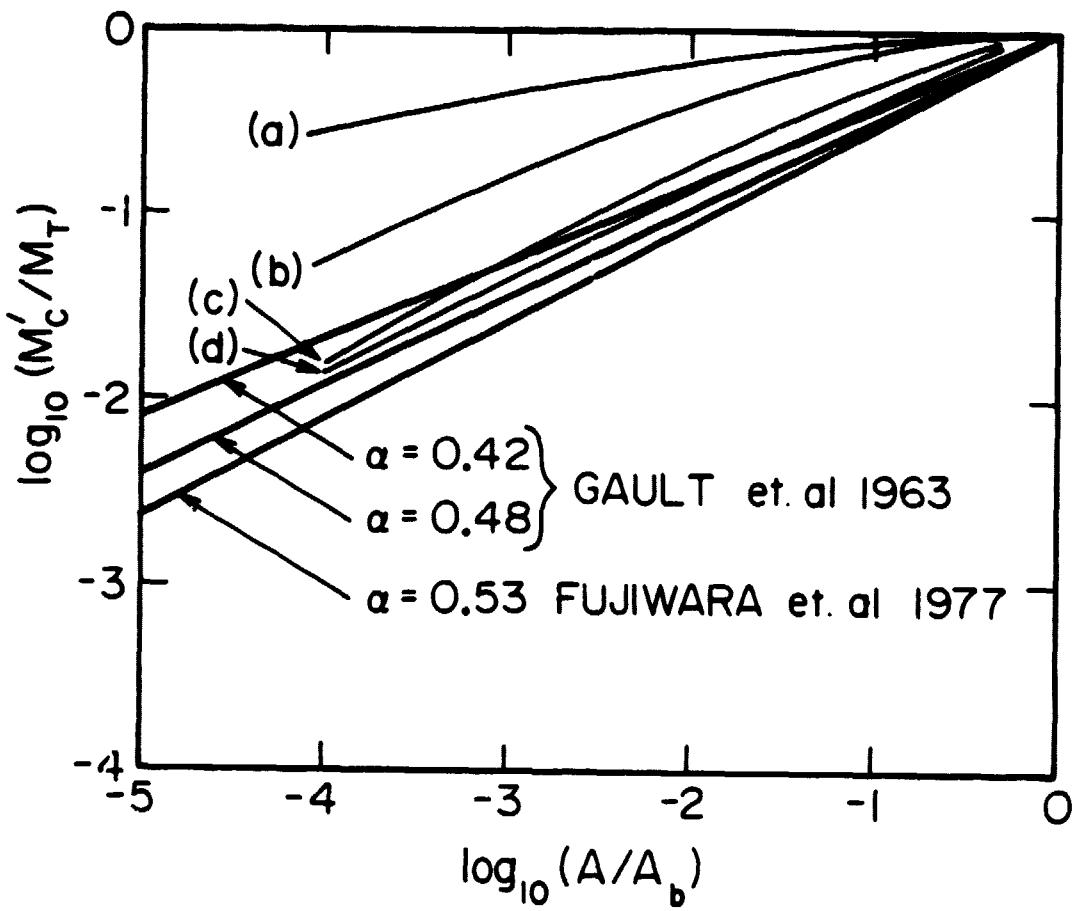
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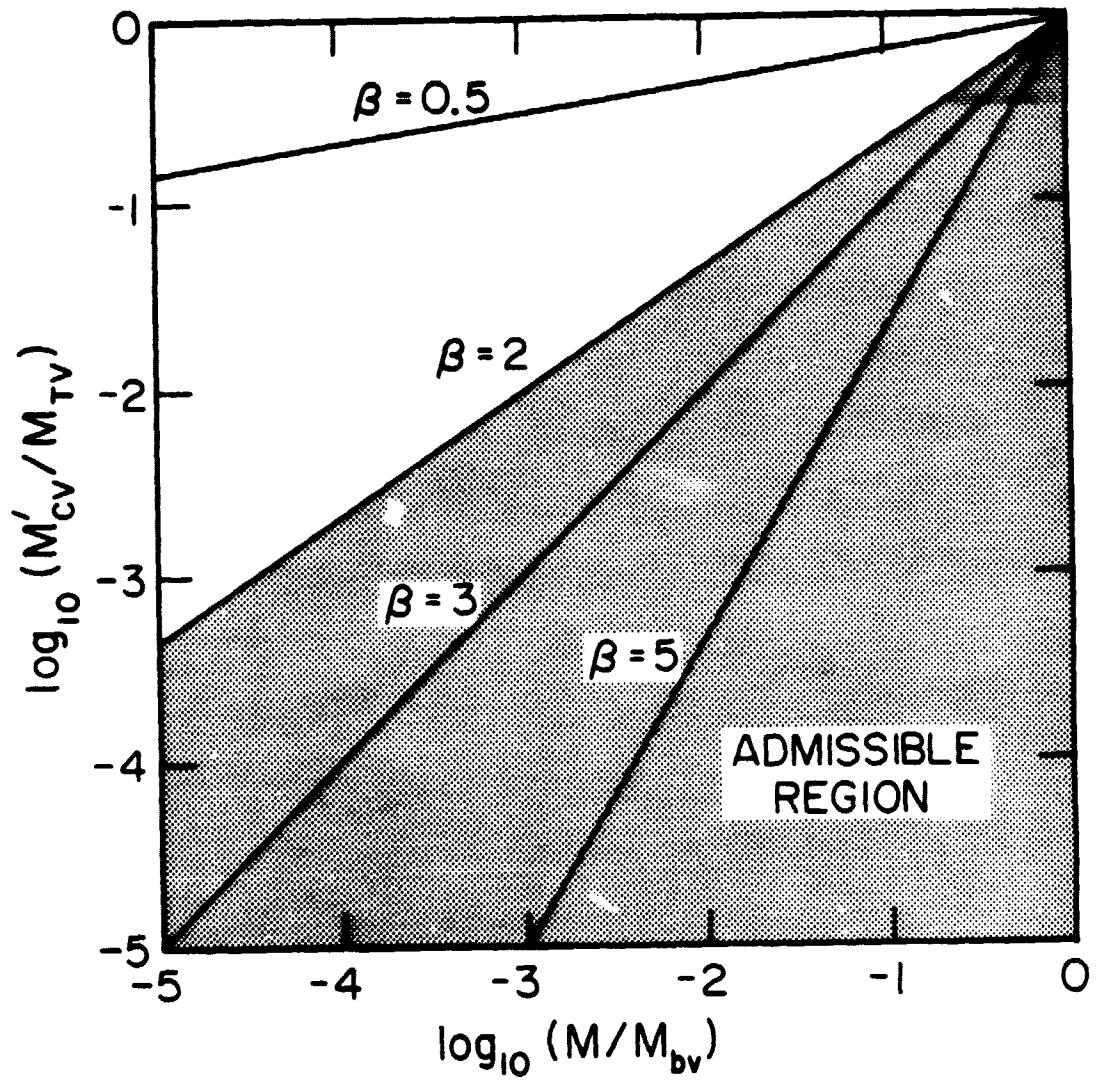
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